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Document 12.3
Evaluation and Control of Facility Airborne Effluents

Recommended for approval by the ES&H Working Group

Approved by: Robert W. Kuckuck
Deputy Director for Operations

New document or new requirements

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12.3

Evaluation and Control of Facility Airborne Effluents*

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* **Editorial revision**

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Evaluation and Control of Facility Airborne Effluents

1.0 Introduction

This document provides guidance about how to plan for the discharge of radioactive or toxic airborne effluents from buildings. The document is organized to proceed sequentially as follows:

- Selecting air contaminant exposure criteria.
- Air cleaning to avoid discharges.
- Determining how much hazardous material can be discharged in a given time.
- Calculating a minimum stack height.
- Calculating possible exposures from that stack height.
- Determining what to do if the discharge must be made below the minimum stack height.

This document is intended mainly for ventilation system designers and Environment, Safety and Health (ES&H) Team personnel who will review the designs. It is also meant for directorate personnel considering the use of materials that could become hazardous air contaminants so they will know what steps their designers and ES&H Teams will need to follow in support of their planned operation.

This document applies to all situations in which toxic or radioactive airborne effluents are or could be discharged from buildings. It is intended to be used in conjunction with Document 31.1, "Air Quality Compliance" and Document 31.2, "Permitting Air Emission Systems," in the *ES&H Manual.*

This document does not apply to nuisance materials or discharges from heating, ventilation, and air conditioning (HVAC) systems used to ventilate offices or places where minor or transient nuisances exist, such as rest rooms. (For the situations described in the previous sentence, see the latest edition of ASHRAE [American Society of Heating, Refrigeration, and Air Conditioning Engineers], *Ventilation for Acceptable Indoor Air Quality*, Standard 62, for guidance.)

Airborne effluents are considered in hazard classifications as described in Section 2 of Document 3.1, "Safety Analysis Program," in the *ES&H Manual*. The logic is depicted in Figure 1c of that document.

2.0 Process for Compliance and Risk Reduction

2.1 Setting Acceptable Exposure Levels

Routine onsite exposures during routine operations, including exposures of personnel working on roofs, shall not exceed the Occupational Exposure Limits (OELs) for the effluents that are established in Work Smart Standards (WSS). Ventilation systems and the equipment they serve shall also be designed to assure that the concentrations of air contaminants during emergencies do not exceed the following emergency exposure criteria:

- Emergency Response Planning Guidelines (ERPGs) developed by the American Industrial Hygiene Association.
- DOE-developed ERPG equivalents, Temporary Emergency Exposure Limits (TEELs), available at:

  http://tis-hq.eh.doe.gov/web/chem_safety/teel.html

- Locally developed ERPG-equivalents (if ERPGs or TEELs do not exist).

ERPG-equivalents shall be developed to meet the ERPG definitions in the AIHA ERPG series based on the best practical literature review that can be conducted. In most cases these ERPG-equivalents shall be developed using LLNL protocol. However, if time or lack of resources does not permit development of an ERPG-equivalent using LLNL protocol, then the DOE protocol for developing ERPG-equivalents shall be used (see "Methodology for Deriving Temporary Emergency Exposure Limits (TEELs)" at http://www.scapa.bnl.gov/). Requirements for radioactive effluents are found in DOE Order 5480.23 (Nuclear Safety Analysis Reports).

Onsite exposures caused by emergency releases of materials shall be less than the ERPG-2/ERPG-2-equivalent outside of the building in which the release originated, whenever possible and must always be below ERPG-3/ERPG-3-equivalent.

Worst case offsite exposures caused by emergency releases of materials when not controlled by active devices such as stacks or scrubbers shall be less than the ERPG-2/ERPG-2-equivalent. Worst case offsite exposures caused by emergency releases of materials when they are controlled by active devices such as stacks or scrubbers shall be less than the ERPG-1/ERPG-1-equivalent.

In making calculations of concentrations created by emergency releases, follow these guidelines:

Concentrations are first calculated as peak 15-minute average values, and this is the applicable value for all chemicals for which the toxicity effect is immediate (i.e., concentration-dependent, e.g., irritants, corrosives, and any chemical that has a PEL-STEL, PEL-C, TLV-STEL, or TLV-C value [see Section 3.2]).

If this procedure appears to yield overly conservative results for chemicals whose toxic effects depend upon the total quantity of chemical taken into the body (i.e., dose-dependent [see Section 3.2]), then for those chemicals only, the peak 1-hour average concentration may be used as the basis for comparison with the guideline concentrations.

Class D stability and a wind speed of 4.5 m/s (or 50% site-specific meteorology) is used, and no credit may be taken for plume meander or building wake effects.

2.2 Selecting Controls

Controls shall rely on passive rather than active measures, whenever practical. This is a result of DOE safety analysis requirements. Possible passive controls include:

- Dilution of toxic gas in a compatible nontoxic gas in the cylinder mixed by the gas vendor.
- Quantity limits on toxic gases/materials that can be stored or used at a given location.
- Restrictive flow orifices for toxic gases using orifices already installed by the gas vendor before the cylinder is shipped to LLNL.
- Use of all-welded gas delivery lines.

Active controls should be rugged, simple, and easy to verify by user personnel.

Some examples of active controls are

- HEPA filters for particulates.
- Stacks tall enough to clear building and roof turbulence zones and associated ventilation systems.
- Gas monitors.
- Other air cleaning devices.
- Process shut-off devices.

2.2.1 Effluent Treatment

Highly hazardous materials shall be removed (scrubbed) from building effluents whenever practical. Hazardous materials should be scrubbed from building effluents. Air cleaning devices shall be selected to incorporate the following attributes to the maximum attainable extent:

- Efficiency—Air cleaners shall be selected to provide required efficiency, as determined by Hazards Control and/or the Environmental Protection Department and should provide the highest practical level of protection. Efficient and reliable air cleaners have eliminated the need for tall stacks at several LLNL locations.
- Reliability—The most reliable air cleaning mechanism suitable for a job shall be selected. Filters have no moving parts and their failure mechanisms are reasonably well understood while organic vapors can break through carbon adsorber beds at unpredictable times when the adsorber is challenged with several compounds at one time. Liquid scrubbers require equipment to circulate scrubbing liquor while resin bed absorbers do not. Resin bed absorbers are almost as maintenance-free as filters.
- Redundancy—A means of preventing escape of air contaminants shall be provided in case an air cleaner fails. (For example, a HEPA filter can be backed up by a second HEPA filter in series. An air cleaner can be interlocked in a fail-safe manner to the contaminant source and/or air mover, if it is safe to do so.)
- Ease of monitoring performance—Air cleaning equipment shall be selected with built in test devices, if practical and if the test devices are reliable. Air cleaners shall be installed with access and provisions for testing in accordance with manufacturer's directions and established standards of good practice for the air cleaning technology in use. (For example, HEPA filter performance monitoring requires pressure differential measurements using inexpensive, simple instruments and annual penetration testing. Monitoring a carbon bed for breakthrough, if possible for the contaminants of interest, requires continuous electronic surveillance instruments that must be periodically calibrated and serviced by skilled personnel.)
- Serviceability—New air cleaner installations shall allow room and access for servicing, maintenance, testing, and replacement of parts. They must also provide utilities needed for testing, servicing, and maintenance.

Performance requirements of air cleaners shall be set by the ES&H Teams and sometimes regulating agencies. Unless otherwise specified by the area ES&H Team, air cleaners for critical applications, removing radioactive materials or carcinogens from an effluent stream, shall meet the standards for removal efficiency associated with HEPA filters, (that is, 99.97% efficiency as determined by the most rigorous definition of efficiency) and redundancy shall be provided. Air cleaning equipment shall be used, maintained, and tested in strict accordance with manufacturer's directions, permit requirements, and regulatory agreements.

2.3 Dealing with Emissions that Cannot Be Removed

There will be times when it is not practical to remove hazardous materials from an effluent stream.

2.3.1 Evaluating Exposures

The process of estimating releases of effluents to the atmosphere can be broken into three phases:

- Defining the "source term" (i.e., how much material is emitted in a given amount of time).
- Determining if the release point (i.e., the stack discharge) can be located where it is free of turbulence caused by the building, building appurtenances such as equipment penthouses, as well as nearby buildings or trees.
- Estimating exposures to the material at relevant locations:
  - On the roof of the building where work may be done or where an air intake is present.
  - At nearby locations, usually 100 m away.
  - At the LLNL boundaries (including the main site and Site 300).
  - At closest offsite receptor (e.g., day care center).

The estimated exposures are compared with the applicable exposure criteria to determine if the controls are adequate.

Determining Allowable Releases. The materials that could cause significant releases can be determined from:

- ChemTrack inventory.
- Safety plans.
- Firsthand knowledge of the industrial hygienist, building health and safety technicians, health physicists, and environmental analysts.

The quantity of materials used divided by the OEL can be used to calculate a figure of merit to determine which materials need to be evaluated.

Release scenarios can then be defined involving routine or emergency releases. Routine releases can be calculated based on chemical use information supplied by building personnel. Routine release calculations should take active controls, such as hoods discharging through tall stacks or scrubbers, into account.

Emergency release information can be estimated in the first step of the calculation process. Standard models and tools which are known to the ES&H Team industrial hygienists, such as the ALOHA or EPIcode® applications, or health physicists, such as the Hotspot application, should be used to estimate release rates. Emergency releases are usually assumed to occur at ground level, essentially "in the parking lot".

Tools for estimating releases from compressed gas cylinders are described in Appendices B and C. *Technical Guide for Hazards Analysis - Emergency Planning for Extremely Hazardous Substances* [USEPA/USDOT (1987)] gives a method for estimating releases from puddles of liquids. Information relevant to radionuclides and some chemicals is available in DOE HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*.

Determining if the Release Point Is Located Where It Will Not Come Back Down on the Roof. Effluent shall be discharged so it will not come back down on the same roof. This means effluent shall not be released so it:

- Is trapped in the turbulence or high turbulence zone generated on the windward side of a building by air striking that wall as shown in Figure 1.
- Is trapped in the leeward side of the building by air breaking over the roof into the partial vacuum located in the building wake region on the leeward side as shown in Figure 1. The plume from a stack will not be diluted in a reliable and effective manner if it is released in the zone of turbulent airflow around a building.
- Comes back down on the roof downwind of the release point. Using the widely accepted guidance of DOE HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, it is assumed that a plume sags one foot vertically for every five feet of horizontal travel. The height from which the plume sag is calculated is the actual height of the stack plus the "plume rise" resulting from the upward velocity of effluent leaving the stack, provided the discharge velocity is ≥3500 fpm.

The relationship of stack height, plume rise, and plume sag are shown in Figure 1 and explained in more detail in Appendix D. Whenever possible, effluents shall not be discharged so they reach either the turbulence zone or high turbulence zone above a building or the building wake region on the leeward side of a building. This can be done by making the stack tall enough so the plume does not sag into a turbulent flow zone. If there is no alternative to discharging the effluent into a turbulence zone or a building wake, then the protocol specified in Section 2.3.2 and Appendix E of this document shall be followed. The plume is assumed to sag one foot for every five feet of horizontal travel once the plume has stopped rising. These determinations shall consider all wind directions and building faces.

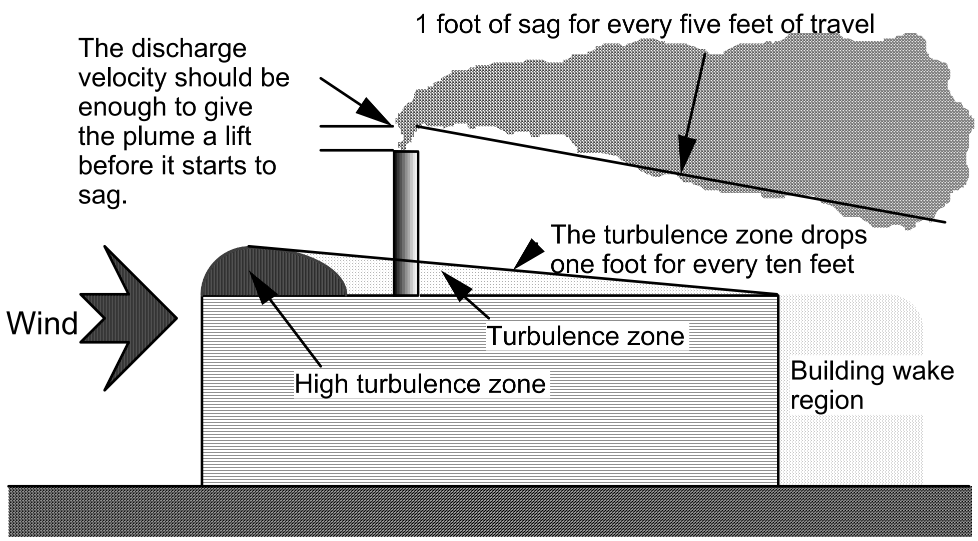


Figure 1. Relationship of stack height, plume rise, and plume sag.

Estimating Exposures. Exposures shall be estimated for the distance of 100 m and at the distance of the nearest fence line.

Hazard classifications of buildings per Document 2.2, "Managing ES&H for LLNL Work," in the *ES&H Manual* are done by safety analysts. This determination is made assuming a wind velocity 4.5 m/sec wind speeds and Class D meteorological stability. Safety analysis calculations are made using a 1 m/sec wind velocity and Class F meteorological stability. Exposures are modeled using a standard Gaussian dispersion model such as Hotspot, EPIcode or ALOHA at the distances of 100 m from the source and at the distance of the nearest fence line. Releases are assumed to occur at ground level ("parking lot release"). ALOHA is used for estimating source terms of gases and liquids from sources other than cylinders. While the calculations are fast, doing the groundwork needed to use these tools is not. It is necessary to walk the area for extant installations and review plans for new and existing installations to obtain information needed to calculate puddle expanses or other information needed to do calculations with EPIcode or ALOHA. The peak and hour-long average concentrations that would exist during an exposure need to be calculated, whenever practical, at the distances of 100 m and the distance to the nearest fence line.

Exposures Within 100 m. Exposures within 100 m can be estimated in the following ways:

- Using the model for discharge within the zone of building turbulence, which follows in Section 2.3.2, if and when appropriate.
- Using a Gaussian model. This method is fast and the result is satisfactory if the model reveals that concentrations will be acceptable under worst-case conditions because Gaussian models can grossly overestimate exposures at distances below 100 m.
- Using the "ASHRAE" or "Wilson" model [WSS "Airflow Around Buildings", Chapter 14 of *ASHRAE Handbook of Fundamentals* (1993)]. This method is more accurate but is extremely time consuming. Time is required to visit the area to look for buildings, trees, and stands of trees (which are considered to be equivalent to buildings for the purposes of this model). The dimensions of buildings and building separations are determined from Plant Engineering records. Sketches are prepared of the heights and distances of all relevant buildings and trees so the "stretched string distances" called for using ASHRAE methods can be calculated. Then it is possible to perform the calculations, and check them for errors in data entry and logic. The spreadsheet is reproduced, with formulas from the ASHRAE reference, in Appendix F.

2.3.2 Discharge Within Building-Induced Turbulence

If the stack can not be made tall enough to clear the roof or building turbulence, then the worst case dilution can be calculated using the protocol specified in Appendix E.

There are circumstances where no dilution can be assumed to occur and these configurations shall be avoided:

- Discharging effluent in a copse of trees which encloses the building and the discharge.
- Discharging into a cul-de-sac in a building such as a three or four sided area below roof height or the height of architectural screens.
- Discharging into the "high turbulence zone" shown in Figure 1.

3.0 Responsibilities

All workers and organizations responsible for evaluation and control of facility airborne effluents shall refer to Document 2.1, "Laboratory and ES&H Policies, General Worker

Responsibilities, and Integrated Safety Management," in the *ES&H Manual* for a list of general responsibilities. Specific responsibilities are listed below each title.

3.1 Responsible Individual

- Contacts the building ES&H Team to obtain guidance about controlling building discharges during planning stages for new experiments and operations.
- Provides information about material use to the ES&H Team and designers to allow hazard classifications and calculations to be done accurately and rapidly.
- Ensures that airborne effluent systems are designed to meet their requirements.

3.2. ES&H Teams

- Provide hazard classification guidance about buildings.
- Provide guidance about air cleaning requirements and, when applicable, the required efficiency of air cleaners through their environmental analysts, health physicists, and industrial hygienists.
- Provide guidance about permitting, monitoring, and reporting requirements.

3.3 Safety Analysis Staff

- Supports ES&H Teams by providing up-to-date guidance about safety analysis, assisting with dispersion calculations, and keeping current with developments concerning dispersion calculations.

3.4 Plant Engineering/Design Group Retained by Directorates

- Designs airborne effluent systems to comply with applicable federal, state, local, and DOE regulations and good design practice as specified here and in the cited references.

4.0 Work Standards

10 CFR 830, “Nuclear Safety Management”, including Subpart A, Quality Assurance Requirements (830.120 - 830.122) and Subpart B, Safety Basis Requirements (830.200 - 830.207)

DOE STD-3020-97, “Specification for HEPA Filters Used by DOE Contractors,” January 1997.

SEMI S5-93, “Safety Guideline for Flow Limiting Devices”, Semiconductor Equipment and Materials International (1993).

American Society of Heating, Refrigeration, and Air Conditioning Engineers, “Airflow Around Buildings”, Chapter 14 of *ASHRAE Handbook of Fundamentals* (1993).

29 CFR 1910, Subpart Z, “Toxic & Hazardous Substances.”

5.0 Resources for More Information

DOE HDBK-3010-94, Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities (1994)

DOE O 5481.1B, “Safety Analysis Review System” (1987). (This order was rescinded and not replaced. A working group of the Energy Facilities Contractors Group began work on developing replacement guidance. The rescinded order is the best available guidance pending the availability of replacement guidance.)

AIHA Emergency Response Planning Committee, Emergency Response Planning Guidelines Series, American Industrial Hygiene Association, Fairfax, VA.

American Society of Heating, Refrigeration, and Air Conditioning Engineers, Ventilation for Acceptable Indoor Air Quality, Standard 62 (latest edition).

NIOSH (National Institute for Occupational Safety and Health). Documentation for Immediately Dangerous to Life or Health (IDLH) Considerations. U.S. Department of Health and Human Services, Cincinnati. OH; PB 94-195047, National Technical Information Service, Springfield, VA (1994).

National Academy of Sciences, Criteria and Methods for Preparing Emergency Exposure Guidance Level (EEGL), Short-Term Public Emergency Guidance Level (SPEGL) and Continuous Exposure Guidance Level (CEGL) Documents, National Academy Press, Washington DC, (1986).

“Toxic Chemical Hazard Classification and Risk Acceptance Guidelines For Use In D.O.E. Facilities (U) - Recommendations of the Westinghouse M & O Nuclear Facility Safety Committee Subcommittee on Nonradiological Risk Acceptance Guidelines Development”, WSRC-MS-92-206 REV 2 (March 24, 1995)

Rainer, David and William E. Quinn, Am. Ind. Hyg. Assoc. J., 50(8):434-437 (1989)

Craig, D. K., Davis J. S., DeVore, R., Hansen, D. J., Petrocchi, A. J., Powell, T. J., "Alternative Guideline Limits for Chemicals Without ERPGs," American Industrial Hygiene Association Journal, 56:919-925 (1995).

USEPA/FEMA/USDOT, Technical Guide for Hazards Analysis - Emergency Planning for Extremely Hazardous Substances, EPA-OSWER-88-0001, December 1987.

Appendix A

Terms and Definitions

Absorption	A phenomenon where material is completely contained in another, often by a durable chemical reaction, such as an acid gas reacting with a caustic solution on a soaked bed packed with small rings or saddles.
Active control	A control that relies on the presence of power or human intervention to be effective. For example, filtration that requires an electrically powered fan to pull air through the filter.
Adsorption	A phenomenon where a substance is bound, often not in a durable manner, to the surface of another material such as an organic vapor bound to the surface of activated carbon.
Annual limit on uptake (ALI)	Quantity of a single radionuclide, which if inhaled or ingested in one year, would irradiate a person, represented by a reference man, to the limiting value for control of the workplace.
Breathing zone	The air volume around the head of an individual.
Derived air concentration	Airborne concentration obtained by dividing the annual limit on uptake (ALI) by the volume of air breathed by an average worker during a year (2.4×10^3 m^3).
Dispersion model	A mathematical model that describes how a pollutant will behave once it has been discharged into the atmosphere.

Emergency Exposure Guidance Limit (EEGL) [or Acute Exposure Guidance Limit (AEGL)][1]	Similar to Emergency Response Planning Guidelines. A ceiling guidance level (concentration) for single emergency exposure, by workers, usually lasting 1 - 24 hours (infrequent during a lifetime). EEGL exposure is permissible only if it is not expected to cause irreversible harm or seriously affect judgement or performance. Developed by the Committee on Toxicology of the National Research Council to support defense/space related programs.
Emergency Response Planning Guideline (ERPG)	The maximum concentration of a pollutant a person could be exposed to for about an hour one or a few times in a lifetime. A committee chartered by the American Industrial Hygiene Association determines these values. See the pdf document "Methodology for Deriving Temporary Emergency Exposure Limits (TEELs)" at http://www.scapa.bnl.gov/ for further information.
Gaussian model	A discharge model that assumes the concentration of pollutant to the sides of the centerline of the effluent plume decrease in the manner of a normal probability distribution or "Gaussian curve."
Hazardous material	A material that is radioactive, toxic/highly toxic, flammable/explosive, or biohazardous.
HEPA filter	High efficiency particulate air filter. A throwaway, extended-media, dry type filter with a rigid casing enclosing the full depth of the pleats. The filter shall exhibit a minimum efficiency of 99.97% when tested at an aerosol of 0.3 micrometers diameter.
Highly hazardous material	Radioactive materials, carcinogens, biohazardous materials, and acutely hazardous materials.

1 **The National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances (NAC/AEGL Committee) is developing Acute Exposure Guideline Levels (AEGLs) on an ongoing basis.**

Immediately Dangerous to Life or Health Conditions (IDLH)	An atmospheric concentration of any toxic, corrosive, or asphyxiant substance that poses an immediate threat to life or would cause irreversible or delayed adverse health effects or would interfere with an individual's ability to escape from a dangerous atmosphere.
Meteorological stability class	A mathematical value of the parameters used to calculate Gaussian dispersion values. There are seven classes, A through F, developed by Pasquill and Gifford.
Occupational Exposure Limits (OELs)	The maximum concentration of an air contaminant to which working people can be exposed according to an accepted source. Accepted sources are typically an OSHA Permissible Exposure Limit (PEL), Threshold Limit Value (TLV), or derived air concentration (DAC) for radionuclides. In some cases, it may be necessary to use a limit derived by another reputable organization or a limit developed locally at LLNL.
Passive control	A control that requires no power or human intervention to work after it has been installed. Examples are restrictive flow orifices and all welded gas delivery lines.
Permissible Exposure Limit—Ceiling Value (PEL-C)	An employee's exposure to any substance with an OSHA exposure limit that has a ceiling limit shall at no time exceed the exposure limit given for that substance. If instantaneous monitoring is not feasible, then the ceiling shall be assessed as a 15-minute time weighted average exposure which shall not be exceeded at any time during the working day.
Permissible Exposure Limit—Short Term Exposure Limit (PEL-STEL)	The employer shall ensure that no employee is exposed to an airborne concentration of a material having a short-term exposure limit as determined over a sampling period of fifteen minutes.
Permissible Exposure Limit—Time Weighted Average (PEL-TWA)	An employee's exposure to any substance having a PEL-TWA shall not exceed the 8-hour Time Weighted Average for that substance in any 8-hour work shift of a 40-hour workweek.

Restrictive Flow Orifice (RFO)	A small round opening of known diameter provided by the vendor of a compressed gas cylinder that limits the maximum attainable flow rate from that cylinder.
Short-Term Public Emergency Exposure Guidance Level (SPEGL)	A level (concentration) suitable for unprotected, single, short-term emergency exposure, of the general public, taking into account their wide range of susceptibility. Included are children, the aged, and persons with serious debilitating diseases. Effects of exposure on the fetus and on the reproductive capacity of men and women, should also be considered.
Stretched string distance	The distance between two points, separated by uneven features, that would be measured by a string stretched between them.
Temporary Emergency Exposure Limits (TEELs)	Developed by the DOE Subcommittee on Consequence Assessment and Protective Actions (SCAPA). Recognizing that ERPGs exist for a limited number of chemicals, DOE SCAPA developed TEELs so that DOE facilities could do complete hazard analysis and consequence assessments, even for chemicals lacking ERPGs.
Threshold Limit Value—Ceiling (TLV-C)	The concentration that should not be exceeded during any part of the working exposure.
Threshold Limit Value—Short Term Exposure Limit (TLV-STEL)	The concentration to which it is believed that workers can be exposed continuously for a short period of time without suffering from 1) irritation, 2) chronic or irreversible tissue damage, or 3) narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue or materially reduce work efficiency, and provided that the daily TLV-TWA is not exceeded.
Threshold Limit Value—Time Weighted Average (TLV-TWA)	The time-weighted average concentration for a conventional 8-hour workday and a 40-hour workweek, to which it is believed that nearly all workers may be repeatedly exposed, day after day, without adverse effect.

Appendix B

Calculating Flow Rates from a Leaking Cylinder by Rainer and Quinn's Method

(From David Rainer and William E. Quinn, *Am. Ind. Hyg. Assoc. J.*, 50(8):434–437 [1989])

Flow Rate (lpm) = Pressure (psi) × Orifice regression relationship × Flow rate factor

Orifice regression relationships:

6 mil orifice = 0.0157

10 mil orifice = 0.0366

30 mil orifice = 0.3368

$$\text{Other size orifices} = \left(\frac{\text{size of unknown orifice}}{\text{size of next smallest known orifice}}\right)^2 \times \text{orifice regression factor of next smallest known orifice}$$

$$\text{Flow rate factor} = \frac{1}{(\text{nitrogen factor})^{0.5}}$$

Where

$$\text{Nitrogen factor} = \frac{\text{mol. wt. }_{\text{gas}}}{28.014}$$

Therefore

$$\text{Flow rate factor} = \frac{1}{\left(\text{mol wt }_{\text{gas}}/28.014\right)^{0.5}}$$

Table B-1. Molecular weight, nitrogen factor, and flow rate factor of common semiconductor process gases.

	Molecular weight	N_2 Factor	Flow Rate Factor
.0025% Diborane, Ar	39.949	1.426	0.837
10% Phosphine, Ar	39.353	1.405	0.844
5% Dib, N_2	27.997	0.999	1.000
5% Fluorine, He	5.703	0.204	2.216
5% HCl, 1% H_2, Neon	20.812	0.743	1.160
5.23% Cl_2, Argon	41.567	1.484	0.821
Ammonia	17.031	0.608	1.283
Argon	39.948	1.426	0.837
Arsenic pentafluoride	169.914	6.065	0.406
Arsine	77.945	2.783	0.600
Boron trichloride	117.169	4.183	0.489
Boron trifluoride	67.806	2.420	0.643
Chlorine	70.905	2.531	0.629
Diborane	27.67	0.988	1.006
Disilane	62.219	2.221	0.671
Fluorine	37.997	1.356	0.859
Germane	76.642	2.736	0.605
HCl	36.461	1.302	0.877
Helium	4.003	0.143	2.645
Hydrogen	2.016	0.072	3.728
Hydrogen selenide	80.976	2.891	0.588
Neon	20.18	0.720	1.178
Nitric oxide	30.006	1.071	0.966
Nitrogen	28.014	1.000	1.000
Nitrogen trifluoride	71.002	2.535	0.628
Nitrous oxide	44.013	1.571	0.798
Phosphorous pentafluoride	125.966	4.497	0.471
Phosphine	33.998	1.214	0.908
Silane	32.117	1.146	0.934
Silicon tetrachloride	169.896	6.0647	0.406
Silicon tetrafluoride	104.079	3.7157	0.519
Tungsten hexafluoride	297.83	10.631	0.307

Appendix C

SEMI Method of Calculating Flows through Critical Orifices with Known Characteristics

[From SEMI S5-93, "Safety Guideline for Flow Limiting Devices", Semiconductor Equipment and Materials International (1993)]

Calculate flow at specified pressure:

The flow through an orifice, affected by pressure Q_{press}, is as follows:

$$Q_{press} = \frac{(P_i + P_{atm}) \times Q_d}{P_f + P_{atm}}$$

where:

P_i = initial cylinder pressure (psig)

P_{atm} = 14.7 psi

Q_d = the known flow of air through the orifice

P_f = final cylinder pressure (usually 100 psig)

Adjust flow for specific gravity of gas:

$$Q = \frac{Q_{press}}{G_{sp}^{\ 0.5}}$$

where:

$$G_{sp} = \text{specific gravity of gas} = \frac{\text{mol. wt.}_{\text{gas}}}{28.996}$$

This is equivalent to Rainer and Quinn's flow rate factor, except the values are normalized to the molecular weight of air rather than nitrogen. (See Appendix B for information about Rainer and Quinn's flow rate factor.)

SEMI recognizes three sizes of orifices: "A", "B", and "C". Their properties are summarized in Table C-1.

Table C-1. Properties of the three sizes of orifices recognized by SMI.

Orifice designation	**Q_d (slpm)**	**Maximum flow @ 1019 psi (slpm)**	**Maximum flow@ 2038 psi (slpm)**
A	1.0 - 2.0	17.7	35.2
B	3.0 - 4.9	43.4	86.3
C	6.0 - 8.0	70.9	140.8

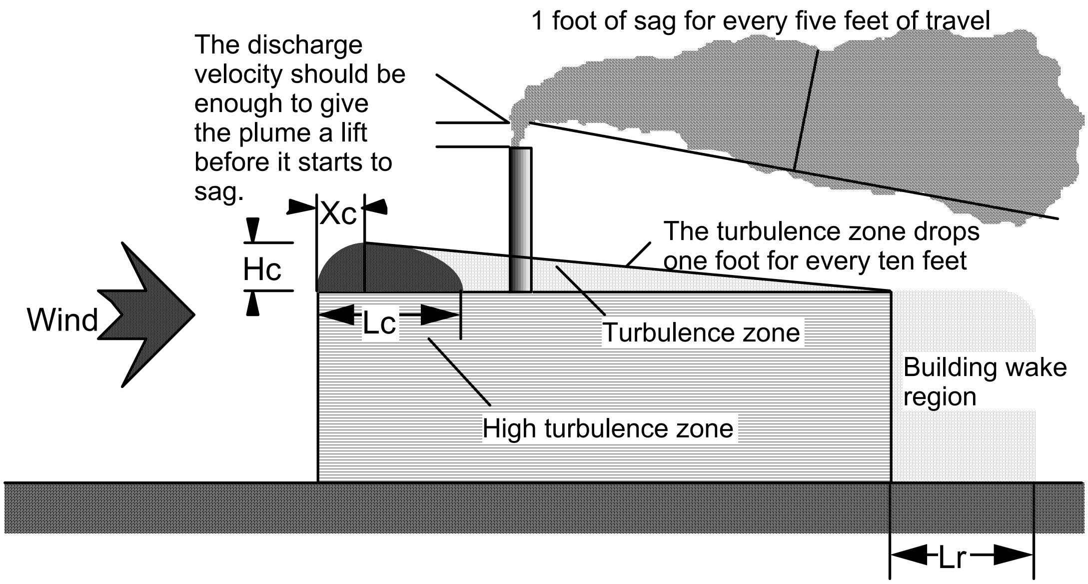
The values for the square roots of the specific gravities of gases, $G_{sp}^{0.5}$, normalized to that of air, are shown in Table C-2.

Table C-2. Square roots of specific gravities of gases normalized to that of air.

Compound	Molecular Weight	G_{sp}	$G_{sp}^{0.5}$
.0025% Diborane, Ar	39.949	1.378	1.173
10% Phosphine, Ar	39.353	1.358	1.165
5% Dib, N_2	27.997	0.966	0.983
5% Fluorine, He	5.703	0.197	0.443
5% HCl, 1% H_2, Neon	20.812	0.718	0.847
5.23% Cl_2, Argon	41.567	1.434	1.197
Ammonia	17.031	0.587	0.766
Argon	39.948	1.378	1.174
Arsenic pentafluoride	169.914	5.860	2.421
Arsine	77.945	2.688	1.640
Boron trichloride	117.169	4.0401	2.010
Boron trifluoride	67.806	2.338	1.529
Chlorine	70.905	2.445	1.564
Diborane	27.67	0.954	0.977
Disilane	62.219	2.146	1.465
Fluorine	37.997	1.310	1.145
Germane	76.642	2.643	1.626
HCl	36.461	1.257	1.121
Helium	4.003	0.138	0.372
Hydrogen	2.016	0.070	0.264
Hydrogen selenide	80.976	2.793	1.671
Neon	20.18	0.696	0.834
Nitric oxide	30.006	1.035	1.017
Nitrogen	28.014	0.966	0.983
Nitrogen trifluoride	71.002	2.449	1.565
Nitrous oxide	44.013	1.518	1.232
Phosphorous pentafluoride	125.966	4.344	2.084
Phosphine	33.998	1.173	1.083
Silane	32.117	1.108	1.052
Silicon tetrachloride	169.896	5.859	2.421
Silicon tetrafluoride	104.079	3.589	1.895
Tungsten hexafluoride	297.83	10.271	3.205

Appendix D

Determining the Dimensions of Turbulence Zones Around Buildings



Referring again to the drawing of Figure 1, reproduced here with graphic definitions of terms, the roof and building wake dimensions are all related to a scaling length, R, which has the following dimensions:

R = major dimension of building face struck by wind$^{1/3}$ × minor dimension of the building face struck by wind$^{2/3}$

The roof wake has the following dimensions:

Height above the roof—

Hc = 0.22R

Setback distance—

Xc = 0.5 R

Length of roof recirculation region—

Lc = 0.9 R

The building wake has the following dimensions:

Height—

H = height of building

Length—

Lr = 1.0 R

Appendix E

Determining Minimum Dilution When Effluents Must Be Discharged Into the Turbulence Zone Above a Roof or a Building Wake Region

If the stack cannot be made tall enough to clear the roof or building turbulence, then the worst case dilution can be calculated. The worst case dilution, D_W, of the stack effluent resulting from traveling over distance can be estimated using the following formula:

$$D_w = (1 + 0.132D_{sd})^2$$

where:

D_{sd} = Distance from stack to receptor measured in *distance units*, where one distance unit = the "stretched string" distance from the stack opening/square root of stack area, in matching units. It is assumed that the breathing zones of people are 5 ft above the surface they could stand on.

There are circumstances where no dilution can be assumed to occur and these configurations shall be avoided:

- Discharging effluent in a copse of trees which encloses the building and the discharge.
- Discharging into a cul-de-sac in a building such as a three or four sided area below roof height.
- Discharging into the "high turbulence zone" shown in Figure 1.

The worst-case dilutions are listed in the following table:

Distance, D_{sd} (Distance units)	Dilution, D_W	Distance, D_{sd} (Distance units)	Dilution, D_W	Distance, D_{sd} (Distance units)	Dilution, D_W	Distance, D_{sd} (Distance units)	Dilution, D_W
0	1	20	13.25	40	39.45	60	79.57
1	1.28	21	14.23	41	41.11	61	81.94
2	1.60	22	15.24	42	42.82	62	84.35
3	1.95	23	16.29	43	44.57	63	86.79
4	2.33	24	17.37	44	46.35	64	89.26
5	2.76	25	18.49	45	48.16	65	91.78
6	3.21	26	19.64	46	50.01	66	94.32
7	3.70	27	20.83	47	51.90	67	96.90

Distance, D_{sd} (Distance units)	Dilution, D_w	Distance, D_{sd} (Distance units)	Dilution, D_w	Distance, D_{sd} (Distance units)	Dilution, D_w	Distance, D_{sd} (Distance units)	Dilution, D_w
8	4.22	28	22.05	48	53.82	68	99.52
9	4.79	29	23.31	49	55.77	69	102.2
10	5.38	30	24.60	50	57.76	70	104.9
11	6.01	31	25.93	51	59.78	71	107.6
12	6.68	32	27.29	52	61.84	72	110.3
13	7.38	33	28.69	53	63.94	73	113.1
14	8.11	34	30.12	54	66.06	74	116.0
15	8.88	35	31.58	55	68.23	75	118.8
16	9.68	36	33.09	56	70.43	76	121.7
17	10.52	37	34.62	57	72.66	77	124.6
18	11.40	38	36.19	58	74.93	78	127.6
19	12.31	39	37.80	59	77.23	79	130.6

Appendix F

Doing ASHRAE Chapter 14 Calculations

[From American Society of Heating, Refrigeration, and Air Conditioning Engineers, "Airflow Around Buildings", Chapter 14 of *ASHRAE Handbook of Fundamentals* (1993).]

Introduction

This appendix describes how to do gas dilution calculations in accordance with Chapter 14 of *ASHRAE Handbook of Fundamentals*. The process begins with gathering the necessary information. The information is used to prepare diagrams that are used to calculate separation distances and the "stretched string distances" which show how far the effluent travels. The results of these distance calculations are then plugged into a series of equations to calculate dilution.

Before you begin

You will need:

- Architectural drawings of buildings of interest which show external building dimensions.
- Overhead drawings showing spacing between buildings.
- Visual reconnaissance to estimate heights of trees.
- Estimated concentration of contaminant as it leaves the stack.

About the presolved example

The presolved example is shown in the following spreadsheet. You enter items shown in bold. References are made to equations in Chapter 14 of the *ASHRAE Handbook of Fundamentals*. Figure E-1 depicts the example. This method was developed by David J. Wilson and is also known as the "Wilson model."

Always:

- Treat trees as though they are buildings (i.e., solid objects, which is what they are to air currents).
- Assume that the *effective height* (i.e., the height difference between stack height and the height of an object the plume is flowing over) can increase but never decrease as you move away from the source.

Use this model in two ways:

- To determine the concentration of contaminant when it reaches a receptor for a fixed configuration of building, stack, wind, and receptor location.
- To determine how much toxic material can be released; do this by having the spreadsheet calculate the lowest dilution. The dilution at the stack multiplied by this figure is the minimum available dilution. Vary the release rates versus the exposure criterion to determine how much contaminant can be released from the building.

First way:

This assumes you know the building layout and operation. You are trying to estimate exposures or figure a minimum stack height.

You always work upwind from all sides of building; that means four sets of calculations and comprehensive drawings.

Enter the data needed for each building side.

A variation of this is to find the stack height that gives adequate dilution. Keep changing C7, adjusting the stretched string distances in C17 as needed, until you reach the dilution you need.

Second way:

This assumes you know the building layout and stack height. You are trying to determine limits to the amounts of toxic materials in the building.

For each of the four sides, enter the data in C1–C5 and C9 and rows 17 and 23. Look at row 33 for the lowest figure of dilution. Iteratively adjust the inputs in rows 17 and 23 to find the lowest dilution.

Use the lowest dilution to calculate lowest total dilution (i.e., what you just figured times the dilution at the mouth of the stack) and use that to calculate exposures. Write down the lowest dilution or otherwise transpose it to a much simpler spreadsheet that can be used to calculate exposures based on various releases of toxic materials from that point.

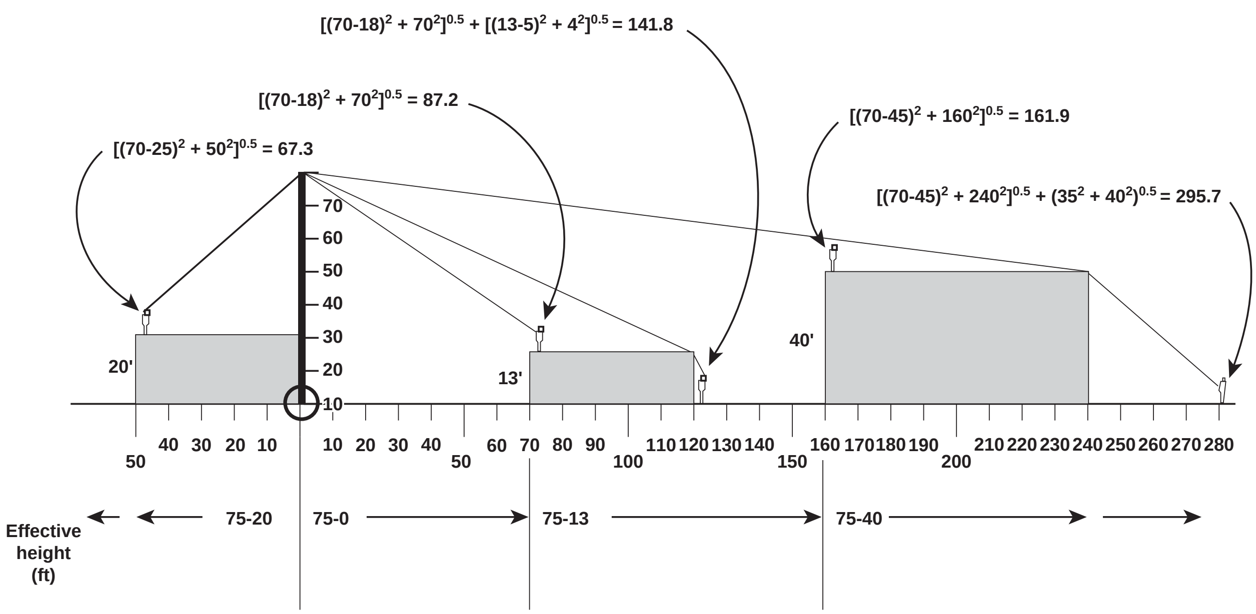


Figure E-1. Drawing of scenario for presolved diffusion calculation. The numbers above the picture are examples of stretched string distance calculations. It is assumed that a person's nose is about 5 ft above where he/she is standing. A scenario needs to be worked out for each building or group of buildings around the emission point; overhead plant layout drawings can be used to plot distances from source to receptors and architectural drawings can be used to determine building dimensions, particularly heights. Note effective height (the height difference between the emission point and down wind features) can increase, but cannot decrease. Trees should be counted as buildings in determining effective heights.

Annotated 1993 ASHRAE Spread Sheet

	A	B	C	D	E	F	G	H
1	*Larger Bldg. Dimension*	**20**	ft.					
2	*Smaller Bldg. Dimension*	**10**	ft.					
3	*Exhaust flow*	**1000**	cfm					
4	*Exhaust dia.*	**6**	ins.					
5	Exhaust area	0.19635	Ae, in sq. ft.					
6	Exhaust velocity	5092.958	Ve, in fpm					
7	*Stack height*	**25**	S, in ft.					
8	*In stack dilution*	**1000**						
9	Scaling dimension	12.59921	R (eq. 1)	*=$C$1^(1/3)*$C$2^(2/3)*				
10	Max height of edge burble	2.771826	Hc (eq. 2)	*=0.22*$C$11*				
11	Distance to max' height	6.299605	Xc (eq. 3)	*=0.5*$C$11*				
12	Length of edge burble	11.33929	Lc (eq. 4)	*=0.9*$C*11*				
13	Length of building lee side turbulence burble	12.59921	Lr (eq. 5)	*=$C$11*				
14								
15								
16	*Distance*							
17	*Stretched string distance, S*	**10**	**20**	**30**	**40**	**50**	**60**	**70**
18								
19	*C20/($C$6^0.5)* S/Ae^0.5	22.56758	45.1351664	67.7027	90.2703	112.838	135.405	157.973
20	eq. 22 *=$C$7*2.9*(0.0625^(-1/3))*(C22^(-2/3))* Ucrit, o	4660.345	2935.83333	2240.46	1849.46	1593.82	1411.4	1273.56
21	eq. 23 *=1+7*(0.0625^(2/3))*C22^(1+(1/3))* Dcrit,o	71.30693	178.162356	305.2	447.421	602.116	767.537	942.446
22								
23	*Obstacle height, ft.*	**10**	**10**	**10**	**10**	**10**	**10**	**10**
24	*=$C$8-C26* Effective height, hs, in ft.	15	15	15	15	15	15	15
25								
26	text of p. 14.13 *=12.6*((C27/C20)^2)* Y = 12.6*(hs/S)^2	28.35	7.0875	3.15	1.77188	1.134	0.7875	0.57857
27	*Entered Y (can't >2)*	**2**	**2**	**2**	**1.7719**	**1.134**	**0.7875**	**0.5786**
28								

	A	B	C	D	E	F	G	H
29	eq. 27 *=C23/(((C30+1)^0.5)-(C30^0.5))* Ucrit	14662.68	9236.90782	7049.08	5541	4025.53	3139.5	2568.84
30								
31	eq. 28 *=C24*C32*(EXP(C30+(C30^0.5)*((C30+1)^0.5)))/C23* **Dcrit**	**19200.6**	**47973.35**	**82181**	**72318**	**22395**	**12291**	**8816.3**
32								
33	*=C35*$C$9* ***Dtot***	***2E+07***	***4.8E+07***	***8E+07***	***7E+07***	***2E+07***	***1E+07***	***9E+06***

	I	J	K	L	M	N	O	P	Q
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17	80	90	100	110	120	130	140	150	200
18									
19	180.541	203.108	225.676	248.243	270.811	293.379	315.946	338.514	451.352
20	1165.09	1077.1	1004.04	942.229	889.127	842.925	802.292	766.227	632.506
21	1125.91	1317.2	1515.72	1720.97	1932.55	2150.1	2373.3	2601.88	3817.85
22									
23	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**
24	15	15	15	15	15	15	15	15	15
25									
26	0.44297	0.35	0.2835	0.2343	0.19688	0.16775	0.14464	0.126	0.07088
27	**0.4430**	**0.35**	**0.2835**	**0.2343**	**0.19688**	**0.1678**	**0.1446**	**0.126**	**0.0709**
28									

	I	J	K	L	M	N	O	P	Q
29	2174.98	1888.7	1672.09	1502.89	1367.23	1256.13	1163.48	1085.05	822.925
30									
31	**7281.1**	**6517.6**	**6126.7**	**5940.8**	**5879.3**	**5898.9**	**5974.6**	**6090.9**	**7023.3**
32									
33	***7E+06***	***7E+06***	***6E+06***	***6E+06***	***6E+06***	***6E+06***	***6E+06***	***6E+06***	***7E+06***